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Deficiency of Adaptive Control of the Binocular Coordination of Saccades in Strabismus

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Disconjugate (different in the two eyes) oculomotor adaptation is driven by the need to maintain binocular vision. Since binocular vision is deficient in strabismus, we wondered whether oculomotor disconjugate adaptive capabilities are deficient in such subjects. We studied eight adult subjects with constant, long-standing convergent strabismus of variable angles (4–30 prism D). No subject had severe amblyopia. Binocular vision was evaluated with stereoacuity tests. Two subjects had peripheral binocular vision and gross stereopsis; two other subjects had abnormal retinal correspondence and abnormal or pseudo gross stereopsis. In the other subjects binocular vision and stereopsis were absent. To stimulate disconjugate changes of saccades, subjects viewed for 20 min an image that was magnified in one eye (aniseikonia). Subjects with residual peripheral binocular vision and even subjects with pseudo or abnormal binocular vision showed disconjugate changes of the binocular coordination of their saccades; these changes reduced the disparity resulting from the aniseikonia. In contrast, for subjects without binocular vision the changes were not correlated with the disparity induced by the aniseikonia. Rather, these changes served to improve fixation of one or the other eye individually. © 1997 Elsevier Science Ltd

Saccades Disconjugacy Aniseikonia Binocular vision

INTRODUCTION

Recent studies (Kapoula *et al.*, 1995; Van der Steen & Bruno, 1995) showed that normal subjects, when exposed to an image whose size is made unequal in the two eyes (aniseikonia), are capable of altering the conjugacy of their saccades; within a period of few minutes saccades become unequal in the two eyes. The induced saccade amplitude inequality reduces the disparity and allows binocular vision around any point of fixation, despite the aniseikonia. The disconjugacy can persist even under monocular viewing (in the absence of any disparity cues), which indicates the presence of a fast learning mechanism. The mechanisms underlying such learning are not clear.

Evidence supporting the idea that the disparity vergence system is involved in adaptive changes of saccade conjugacy has been presented by Lewis *et al.* (1995) in patients with trochlear nerve pareses. These patients showed several deficits: position-dependent vertical static eye misalignment, hypometric saccades in the paretic eye. After strabismus surgery, only patients who prior to surgery had large vertical vergence movements were able to return to a more conjugate coordination of saccade amplitudes. In an earlier study (Oohira & Zee, 1992), normal monkeys wore for 15 days a combination of prisms calling for convergent or divergent disconjugacy depending on gaze direction. Most monkeys showed appropriate, orbital specific disconjugate adaptation of both static and dynamic alignment of saccades. One monkey did not fuse the targets in the left visual field viewed by the 5 prism D base-out prism; instead, in this part the animal showed some adaptive phoria response to the 2 prism D based out prism and gradually lost this response as the eyes moved more to the left. This suggested that fusion is an important element for disconjugate adaptation in normals.

How tightly sensory fusion and oculomotor disconjugate adaptive capabilities are linked is not known. A recent study by Kapoula *et al.* (1996) showed that human microstrabismic subjects who lack bifoveal fusion, when exposed to aniseikonia are able to change quickly and appropriately the conjugacy of their saccades. This study suggests that peripheral fusion is sufficient to achieve such disconjugate adaptive changes. The goal of the present study was to examine the degree of binocular vision necessary to stimulate disconjugate oculomotor adaptation in subjects with different degrees of strabismus. In the companion report (Kapoula *et al.*, 1997, this issue, pp. 2757–2766), we found that in subjects with

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TABLE 1. Clinical characteristics of subjects with convergent strabismus

Subject	Sex	Age (yr)	Corrected visual acuity	Angle of strabismus (prism D)	Preferred eye	Surgical, or toxin treatment	Time from last treatment	Stereoacuity	Prism worn during the experiment
DB	M	38	RE:20/25 LE:20/25	4-ET	—	Toxin RE	3 yr	240"	2 out RE
MG	M	36	RE:20/25 LE:20/20	7-ET	—	Surgery LE Toxin RE	13 yr 4 yr	3000"	5 out RE
SH	M	22	RE:20/25 LE:20/30	12–18-ET	—	—	—	3600"	—
WG	M	46	RE:20/25 LE:20/25	12–16-ET	LE	—	—	3600"	—
FH	F	24	RE:20/25 LE:20/20	22-ET 5 hyper	LE	Surgery LE	3 yr	—	2 out RE
PB	M	28	RE:20/40 LE:20/20	25-ET	LE	Surgery LE Toxin RE	4 yr 6 yr	—	22 out RE
BM	F	39	RE:20/20 LE:20/20	28-ET 5 hyper	LE	Surgery RE, LE	10 yr	—	22 out RE 5 down LE
TG1	M	29	RE:20/40 LE:20/20	30-ET	LE	Surgery RE	10 yr	—	15 out RE
TG2	M	30	RE:20/40 LE:20/20	14-ET	LE	Toxin RE	10 months	—	10 out RE

LE, RE, left eye, right eye; ET, esotropia. All subjects had good visual acuity in both eyes. All but two subjects (SH and WG) had eye surgery or botulinum toxin injection at least 10 months before the oculomotor test. Subject TG was examined twice with an interval of 1 yr. The second time his squint was considerably reduced due to botulinum treatment.

small strabismus the inherent disconjugacy of saccades is only slightly larger than that known in normals. In contrast, subjects with large strabismus without any binocular vision exhibited larger and more variable saccade disconjugacy, dependent on the direction and on the amplitude of the saccades, as well as on the orbital eye position. We attributed these differences to reduced oculomotor adaptive capabilities in subjects with large strabismus. The present study tests this hypothesis experimentally in three types of subjects: subjects with small strabismus who preserve peripheral binocular fusion; subjects with intermediate strabismus with abnormal retinal correspondence (see below) and pseudo or abnormal binocular vision; subjects with large strabismus who have no binocular vision at all. The subjects with small strabismus and those with large strabismus participated in the prior study (Kapoula *et al.*, 1997). To stimulate disconjugate adaptation of saccade amplitude all subjects were exposed to an image size inequality (aniseikonia). This led to significant and persistent changes in the inherent binocular coordination of the saccades. For subjects who had residual binocular vision and even for subjects with abnormal binocular vision the changes were appropriate to the disparity resulting from the image size inequality. In contrast, for subjects with no binocular vision the changes were not related to the disparity due to aniseikonia.

METHODS

Subjects

General characteristics. Eight subjects (one female and seven male) were tested. The angle of the squint and other important clinical characteristics are shown in Table 1. No subject had a history of paralytic strabismus. All but two subjects (SH and WG) had strabismus eye surgery and/or botulinum toxin in their extraocular muscles. All the treatments were done long ago and none of our subjects had muscular paresis at the time of our experiment.

Ocular dominance and binocular vision capability. Ocular dominance was tested with the 4 prism D base-out prism test. Subjects with small strabismus (DB, MG) and subject SH with intermediate strabismus, could alternate the fixating eye easily and no clear eye preference could be found. For all other subjects the left eye was the dominant eye. Subject WG had a fixed scotoma of about 9 prism D in the right eye (measured by several tests: Bagolini striated glasses, 4 prism D base-out prism, synoptophore). He also exhibited a V syndrome: the squint convergent angle was 16 prism D at eye level, about 30 prism D for down gaze and only 12 prism D for up gaze. The state of binocular vision was evaluated with tests for stereoscopic depth discrimination. For subjects with small strabismus, stereoacuity was present although below normal values: for subject DB the stereoacuity threshold was 240 sec of arc (at the TNO random dot test for stereoacuity); subject MG had only gross stereopsis (3000 sec of arc with the Titmus, fly test). Subjects with intermediate strabismus (SH and WG), had stereopsis with neither the TNO, nor with the Titmus test. However, at the synoptophore, both subjects could describe a rough depth perception. We used images subtending 10 deg with a stereoacuity threshold of about 3600 sec of arc. Both these subjects had anomalous retinal correspondence (ARC), measured with the Bagolini striated glasses test. ARC is the situation where an extrafoveal retinal area of the squinting eye acquires the same visual direction as the fovea of the fixating eye. The functional significance of ARC is controversial. For Bagolini

(1974), ARC is a sensory adaptation aiming to obtain binocular vision; this point is not shared by others (see Von Noorden, 1990 for a critical review). None of the subjects with large strabismus (FH, PB, BM and TG) showed any evidence for stereoacuity; all tests TNO, Titmus, Worth 4 dot and synoptophore were negative manifesting complete deficiency of binocular vision.

Control subjects. Three healthy emmetropic subjects (MM, MP, ZK) were also tested. They had no history of strabismus and their visual acuity was 20/20 in both eyes. Binocular vision was normal (TNO test: 60 sec of arc or better) and all subjects were right eye dominant. This study was approved by the French ethics committee CCPPRB No. 15.

Eye movement recording

Stimulus presentation and data collection were directed by REX, a software developed for real-time experiments and run on a personal computer (DELL 486P/33). For all but two subjects (SH and WG), horizontal movements of both eyes were recorded simultaneously with a photo-electric device mounted on spectacles (IRIS, SKALAR). Eye position signals were low-pass filtered with a cut-off frequency of 200 Hz and digitized with a 12-bit A/D converter. Each channel was sampled at 500 Hz and stored for off-line analysis.

Adaptation paradigm

This paradigm was applied to all subjects except SH and WG. Subjects were seated 80 cm in front of a flat translucent screen upon which a square random dot pattern (subtending 23 deg) was projected. The head of the subject was stabilized with a bite bar (with an individually fitted dental impression of the subject's upper teeth) and a forehead support. During the experiment, all subjects with small and with large strabismus wore an afocal magnifier of 8% in front of their left eye. For subjects with large strabismus the left eye was the preferred eye. Normal subjects wore the magnifier in front of their right dominant eye. In order to render disparities similar in subjects with small and large strabismus, all strabismic subjects wore a base-out corrective prism in the other eye. The power of the prism (indicated in Table 1) was determined on the basis of preliminary orthoptic tests and evaluation. Intolerance of a complete prism correction and preference for a small correction is a frequent clinical experience. This was the case for subject FH, for whom complete prism correction proved to be very uncomfortable. Thus, this subject wore during the experiment a weak prism of only 2 prism D. Subject BM, in addition to the base-out prism, also wore a base-down prism of 5 D to correct her hyperdeviation. Mounting of the afocal magnifier and of the prism in front of the subjects' eyes was done at the very beginning of the experiment as follows. After a preliminary calibration of the IRIS, system, the experimenter inserted on the IRIS system the corrective prism(s) with the use of a lens holder. A special holder-device allowed insertion of the afocal magnifier in front of the other eye. Calibration and the whole sequence of oculomotor testing conditions was conducted without touching this set-up to avoid head movements and artifacts.

Five markers were placed on the random dot pattern at 0, 5 and 10 deg on either side. The limit of 10 deg was chosen because in a companion report we found the baseline binocular coordination of saccades to be particularly impaired for saccades beyond 10 deg. Subjects were instructed to make horizontal saccades back and forth between the markers. The duration of this training period was 20 min. Because of the magnifier the distance between any two markers was larger in the eye with the magnifier. Consequently, this eye was required to make systematically larger saccades if disparity and diplopia were to be avoided.

Oculomotor testing conditions

Baseline recordings (5 min). Viewing was monocular: left eye viewing, followed by right eye viewing. Two black tissue curtains mounted on the head support allowed change from one condition to the other without causing any head motion. These recordings were also used to extract calibration factors for each eye when it fixated the marker targets.

Training recordings (20 min). Viewing was binocular with the magnifier in one eye and, for most of the strabismic subjects, with a corrective base-out prism in front of the other eye. Saccades were recorded continuously.

Post-training recordings (2 min). To test for the persistence of learned saccade disconjugacy, one of the monocular viewing conditions was repeated again; all subjects viewed with the eye wearing the magnifier.

For subjects SH and WG, a similar experiment was run in the laboratory, where a different arrangement was used to induce aniseikonia. Subjects were seated 1 m from a flat translucent screen. Two projectors were used to provide a random dot pattern to each eye. The beams of the two projectors were polarized 90 deg apart; subjects viewed through filters also polarized 90 deg. The two patterns were centered on the screen: one pattern subtended 35 deg, the other 38.5 deg (10% uniform magnification, left eye pattern for subject WG, right eye pattern for subject SH). As mentioned, no corrective prism was used for these subjects because of their abnormal retinal correspondence. Bagolini (1974), 1976), 1982) found that in esotropic subjects with ARC, wearing a base-out prism may cause an increase of the squint owing to slow eye movements ("eating up the prism"). Bagolini called these movements "anomalous fusional movements" and attributed them to the ARC and to an effort to return to the habitual squint angle where abnormal binocular vision can be obtained. Von Noorden (1990), however, found that this "eating up the prism" phenomenon is not limited to subjects with ARC but can also occur in subjects with normal retinal correspondence. Nevertheless, we preferred to avoid the use of prisms in these two subjects to eliminate the risk of increasing their squint angle. Horizontal eye movements

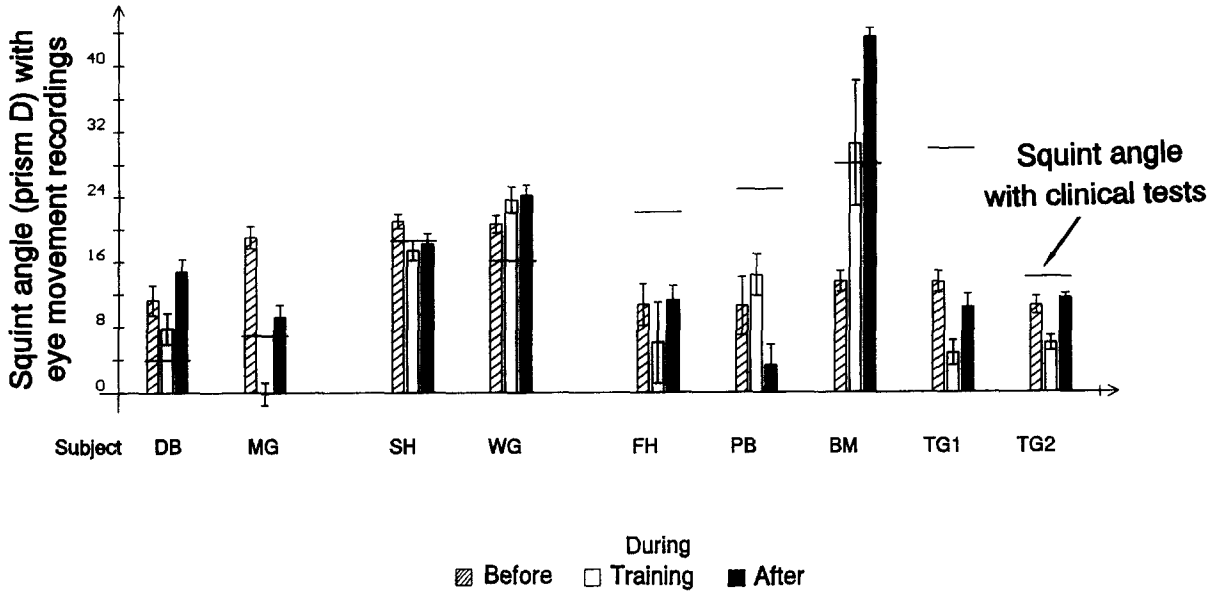

FIGURE 1. Individual means of the squint angle (in prism D) based on eye movement recordings (left–right eye difference at 500 msec after the end of each saccade). Vertical lines are the standard deviation of each mean. Before, after: means for saccades under monocular viewing with the eye wearing the magnifier, recorded before and after training; During training: means for saccades during viewing the aniseikonic images. Means are based on 41–177 saccades for the monocular viewing conditions and on 102–903 saccades for the training condition. Leftward and rightward saccades are grouped together. Horizontal lines indicate (in prism D) the clinical measurement of squint angle (objective angle of deviation at the synoptophore). During all eye movement recordings all but two subjects (SH and WG) wore a corrective base-out prism. For subjects FH, PB, TG1 and TG2 the prism reduced the squint.

were recorded simultaneously with the search–coil magnetic field method. More detailed description on methods and calibration of data have been described in several previous studies (e.g. Kapoula *et al.*, 1995).

Analysis of data

A linear function was used for fitting the calibration data recorded with the IRIS. Since calibration was done with the magnifier on, the target position was specified for each eye individually (it was 8% larger for the eye wearing the magnifier). For each saccade we measured in degrees the disconjugacy (left–right eye difference) in the saccade amplitude, in the post-saccadic drift averaged over the first 160 msec. The term intrasaccadic disconjugacy is used to indicate the disconjugacy of the amplitude of the saccade. Positive values indicate convergent disconjugacy, negative values divergent disconjugacy. Statistical analyses were performed using the Student's *t*-test.

RESULTS

Effect of prism on the squint angle

Figure 1 shows in prism D, the average squint angle measured with eye movement recordings at a time point 500 msec after every saccade. All subjects except SH and WG wore a corrective based-out prism. The horizontal lines indicate (also in prism D) the squint angle (without prism) measured with the synoptophore. Comparison between the two measures indicates the effect of prism on the squint. For all subjects with large strabismus except subject BM, the prism reduced the squint. Recordings before training with unequal images (under monocular viewing) were done after only a few minutes of visual experience with the eye wearing the prism during the preparation period. Thus, the effect of the prism seemed to be fast and was maintained under monocular viewing. The reduction of the squint was more important during binocular viewing (training). In this condition the squint dropped from about 25 to 14 prism D for subject PB, from 30 to 5 prism D (TG1) and from 14 to 6 prism D (TG2). For subject FH the squint was reduced from 22 to 6 prism D, even though this subject had only a small prism correction (2 prism D). We did not test whether the reduction of the squint had any effect on binocular vision and fusion. It is very unlikely, however, that binocular vision can develop in long-standing strabismus after wearing a prism for only 30 min. Pigassou-Albouy & Garipuy (1966) reported that prism therapy in adult strabismus can bring binocular vision but only after several months (5–8 months) of wearing prisms. For subject BM the squint was initially reduced from 28 to 14 prism D. During training, however, and during subsequent monocular viewing, the squint increased again to 30 and to 43 prism D, respectively. This behaviour is an example of the "eating up the prism" phenomenon, and could be due to anomalous slow fusional movements.

For subject DB the squint angle based on eye movement recording was larger than the one measured clinically. It is not clear whether this is due to his neuro-ophthalmological symptoms or to an abnormal over-compensation of the prism (e.g. "eating up the prism").

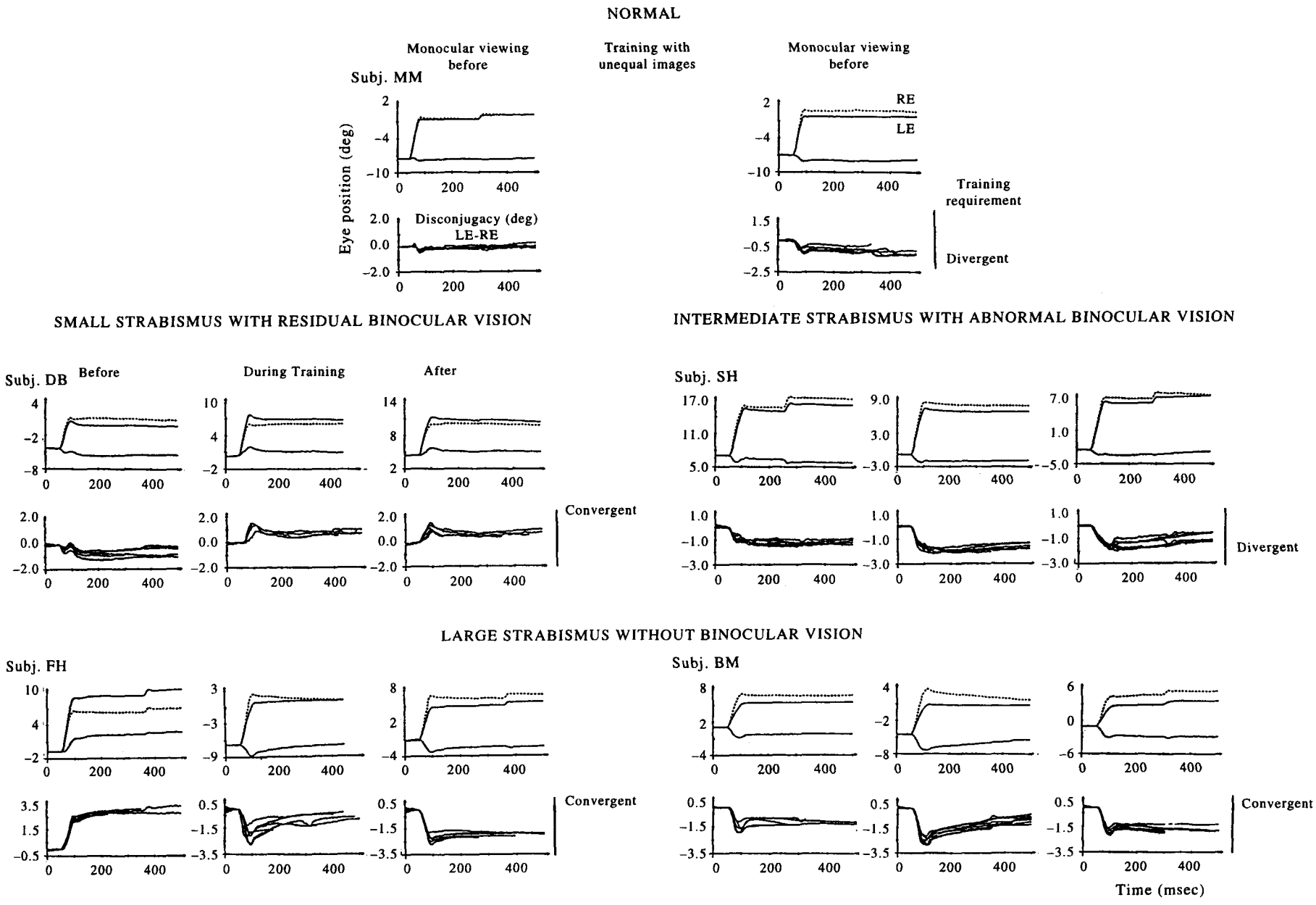

FIGURE 2. Upper plots: typical binocular recordings of rightward saccades before, during and after exposure to unequal images. The solid line is the position trace of the left eye, the dotted line is that of the right eye. The lower trace is the disconjugacy of the saccade (the difference between the left and the right eye ×2). Lower plots: disconjugacy traces from several saccades. All disconjugacy traces are offset to begin at zero. Saccades start at 50 msec and end at approximately 100 msec.

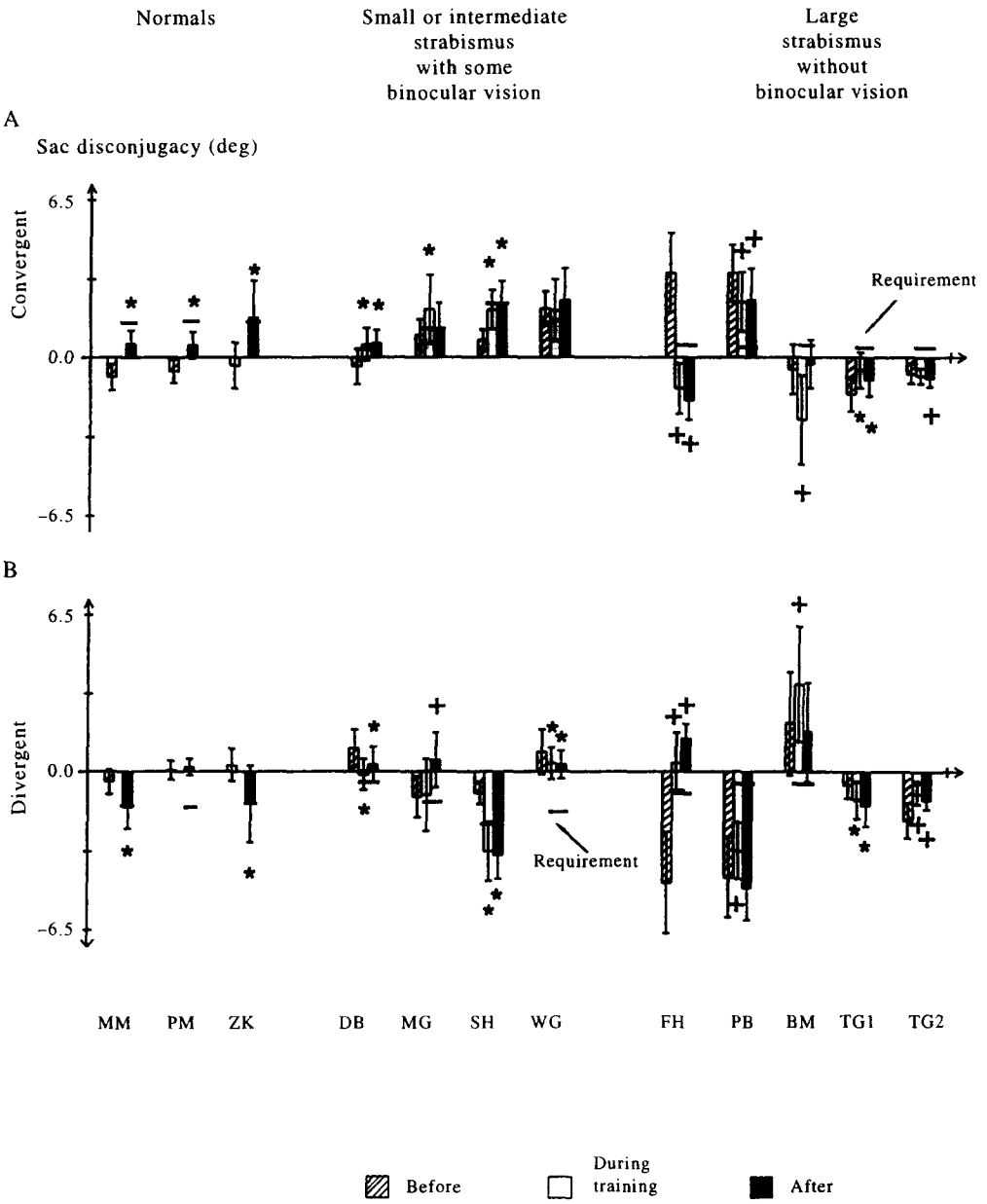

FIGURE 3. Individual means (with their standard deviations) of intrasaccadic disconjugacy before, during and after training. During training they viewed binocularly an image whose size was 8% or 10% larger in one eye. Horizontal lines show the disconjugacy required by the image size inequality. (A) Saccades requiring a convergent disconjugacy (rightward saccades for subjects viewing a larger image with their left eye, leftward saccades for subjects viewing a larger image with their right eye). (B) Saccades requiring divergent disconjugacy. For subjects with large strabismus the disconjugacy requirement was smaller because they were instructed to make small saccades. The mean saccade amplitude (LE + RE/2) was 9, 8, 6 deg for subject FH, before, during and after training; for subject PB these values were 7, 5, 6 deg; for subject BM 7, 5, 5 deg; for subject TG 7, 5, 6 deg in both experiments. Means are based on 20–394 saccades (A) and on 20–509 saccades (B). *A significant change from baseline in the appropriate direction (*t*-test at $P < 0.05$). + A significant change in the opposite direction.

For subject MG the prism nullified the squint during the binocular viewing, training condition. This effect was not maintained in the subsequently recorded monocular viewing condition. In summary, the effect of the prism was to make the squint similar for subjects with small and large strabismus and thus to render disparities similar for the two groups of subjects.

For subject SH, the eye movement based squint estimation and the clinical measure of squint were very similar. These measures were quite different for subject WG, whose squint was unstable even during the clinical evaluation.

Changes of the binocular coordination of saccades

Qualitative observations. Figure 2 shows typical recordings of rightward saccades. The upper panels show individual saccades with their corresponding disconjugacy trace; the lower panels show superimposed disconjugacy traces from several rightward saccades. Before training, rightward saccades from a normal

subject were slightly larger in the right, abducting eye. A few minutes of training were sufficient to cause increased intrasaccadic divergent disconjugacy, as required by the aniseikonic images; the disconjugacy persisted even under subsequent monocular viewing. Post-saccadic drift disconjugacy was negligible.

Before training, subject DB who had small strabismus and residual binocular vision showed transient intrasaccadic disconjugacy, and divergent post-saccadic drift. During training, the left eye that wore the magnifier made larger saccades. This led to substantial convergent intrasaccadic disconjugacy. After training, rightward saccades maintained the increased convergent disconjugacy. Note that post-saccadic drift disconjugacy remained divergent throughout the experiment.

Subject SH, who had intermediate strabismus and abnormal binocular vision, showed abnormally large divergent intrasaccadic disconjugacy for recordings before training. During training, the intrasaccadic divergent disconjugacy increased as required by the image size inequality. After training, while he was viewing monocularly, saccades continued to be larger in the right eye by an amount greater than that observed for his baseline recordings. In contrast, his change in post-saccadic drift was not in the appropriate direction.

Before training, subjects FH and BM who had large strabismus and no binocular vision showed abnormally large intrasaccadic disconjugacy, convergent or divergent. Contrary to the convergent requirement subject FH reversed his baseline convergent disconjugacy to divergent disconjugacy; subject BM increased her baseline divergent disconjugacy instead of decreasing it. Both these maladaptive changes persisted even after training. Post-saccadic drift disconjugacy was almost always convergent before, during and after training.

Quantitative data

Saccade amplitude disconjugacy. Figure 3 shows for each subject the average intrasaccadic disconjugacy before, during and after training with aniseikonic images. For normal subjects data were available only before and after training. Before training all normals showed small divergent disconjugacy within the range of the disconjugacy reported in the literature (Collewijn *et al.*, 1988). After exposure to aniseikonic images, all subjects developed significant intrasaccadic disconjugacy in the appropriate direction that persisted even under subsequent monocular viewing (in the absence of any disparity cues). The post–pre training changes were statistically significant for the majority of cases, and for both saccade directions requiring convergent or divergent disconjugacy.

During training, both subjects with small strabismus and residual peripheral binocular vision (DB and MG), developed intrasaccadic disconjugacy that allowed them to reduce the disparity induced by the magnifier. Three of the four training-pre differences were statistically significant. For subject DB a significant change occurred also for saccades under subsequent monocular viewing.

Interestingly, subjects SH and WG with intermediate strabismus and abnormal binocular vision were also able to make disconjugate changes appropriate to the disparity owing to unequal images. Subject SH showed statistically significant changes from baseline for both saccade directions and for both conditions, before and after training; during training saccade disconjugacy was strongly correlated with the required disconjugacy ($r = 0.76$). Subject WG showed statistically significant changes only for saccades requiring divergent disconjugacy. Thus, the behaviour of these two subjects in response to aniseikonia was very similar to that of normal subjects or of subjects with smaller strabismus and better residual binocular vision.

To our surprise, strabismic subjects without binocular vision also made large changes in the inherent disconjugacy of their saccades. In most cases, the sign of the actual disconjugacy during and after training or the sign of the change of the disconjugacy was not, however, appropriate for the aniseikonic images (crosses indicate statistically significant but inappropriate changes). For subject FH during and after training, disconjugacy of saccades was divergent where it should have been convergent and convergent where it should have been divergent; there was no correlation between the amplitude of the disconjugacy of the saccades and the required disconjugacy. Subject BM's actual disconjugacy and its changes from inherent were also clearly unrelated to the disparity due to the magnifier. Appropriate changes occurred for subject TG in the first session only (TG1). For subjects PB and TG2 divergent requirement, the sign of the training-pre or post–pre change was inappropriate, but the actual disconjugacy during and after training was closer to the requirement than the inherent disconjugacy. However, the criterion of a significant change (training-pre, post-pre) in the correct direction is more reliable than the value of actual disconjugacy, since the change is not influenced by calibration factors. Thus, the overall message from Fig. 3, is that in large strabismus, almost all changes were in the inappropriate direction (cross signs).

In summary, normal subjects and subjects with small or even intermediate convergent squint were all capable of performing appropriate adaptive changes in the binocular coordination of the saccades. In contrast, subjects with large strabismus and no binocular vision made disconjugate changes that were not in the appropriate direction.

Post-saccadic drift disconjugacy

Figure 4 shows individual means of post-saccadic drift disconjugacy for the three testing conditions. The inherent drift was always convergent for normals, mostly divergent for subjects with small strabismus and mostly convergent and large in amplitude for subjects with large strabismus without any binocular vision. Subjects with intermediate strabismus showed mostly divergent drift, similar to subjects with small strabismus. All these characteristics remained, in general, little affected by

decussation of the visual pathways. The egocentric direction of the two eyes could be compared in a binocular sense; if the position and the direction of each eye are accurately computed then diplopia would never occur. Our oculomotor results (Fig. 2) show that the monocularly driven oculomotor changes leave uncorrected, and even create substantial additional, disparity. Yet, our subjects did not report diplopia; utrocular vision could allow avoidance of diplopia but not establishment of a real binocular linkage.

Our finding of changes in the inherent binocular coordination of saccades in subjects with large strabismus and no binocular vision is compatible with the observations of Maxwell *et al.* (1995). In this study, three subjects with intermediate strabismus (<20 prism D) but with deep unilateral amblyopia, and therefore, with no binocular vision, wore a spherical lens of −3 D in front of their amblyopic eye for a week. This caused a change in the inherent disconjugacy of their saccades. Maxwell *et al.* discussed the possibility of a recalibration of the vestibulo-ocular response by the differential retinal slip sensed by the two eyes during a week; vestibular recalibration would be carried over the saccadic system. Another possibility considered by these authors is the hypothesis of utrocular vision allowing independent readjustments for each eye.

Additional observations and remarks

In additional experiments we tested a subject with large divergent strabismus (−42 prism D) and mild unilateral amblyopia (corrected visual acuity RE 20/70, LE 20/40; spectacle correction was RE −11 diopters, LE −7 diopters). The inherent intrasaccadic disconjugacy was relatively small (<0.9 deg). Exposure to aniseikonic images (the 8% magnifier was placed on the left eye and a base-in prism of 40 prism D on the right eye), did not induce any change in the intrasaccadic disconjugacy, even though the prism reduced the squint angle to approx −10 diopters. In a second experiment, the squint was −34 prism D due to botulinum injection (done 10 months earlier). During exposure to aniseikonia (8% magnifier on the left eye) a base-in prism of 22 prism D on the right eye dropped the squint to −2 prism D. Despite his quasi-orthotropia, all the changes in intrasaccadic disconjugacy (2–3 deg large) were in the wrong direction. This supports the idea that at the adult stage, the deficiency of oculomotor adaptations is not related to the type (convergent or divergent) of strabismus, neither to the actual size of the squint. We think that the main reason for such oculomotor failure is the lack of binocular vision. Further support for this comes from our observations on another subject (27 years old) who had convergent strabismus since childhood (initial angle was 35 prism D) and deep amblyopia of the left eye (20/200); her right eye had normal visual acuity (20/20). She underwent eye surgery operation twice (at 7 and 15 yr), and botulinum toxin injection (done 1 yr before our oculomotor testing). At the time of our oculomotor examination her squint was reduced to 8 prism D (esotropia). However, the inherent disconjugacy of her saccades was remarkably large (4–6 deg), the right, non-amblyopic eye was making consistently larger saccades. These observations, admittedly based on one subject, suggest that binocular coordination of saccades is even more deteriorated in strabismics with severe amblyopia. She performed our oculomotor adaptation experiment with the 8% magnifier in front of her right eye. Not surprisingly, this subject did not respond to the disparity induced by the magnifier. Amblyopia in this subject was an additional factor responsible for the paucity of binocular visual linkage.

To recapitulate, we found evidence that at the adult stage, neither the actual size of the squint nor the type of strabismus (divergent or convergent) determine the adaptive oculomotor capabilities. Firstly, we found different oculomotor adaptive capabilities in subjects with small and large convergent strabismus, even though their squint angles were made similar (with the use of the prism). In addition, a subject with almost nullified divergent strabismus failed to adapt to aniseikonia. Furthermore, another subject with small residual convergent squint but deep unilateral amblyopia did not show any response to aniseikonia. One feature common to all these subjects who failed to adapt was a paucity of any binocular visual linkage. Most likely, binocular vision in such subjects could not be restored after wearing a prism for only 20–30 min. As Pigassou-Albouy & Garipuy (1966) reported, in adult strabismics, several months of prism therapy are needed for binocular vision to be restored.

Summary and clinical considerations

All strabismic subjects were capable of making disconjugate changes in their saccades. For subjects with small or intermediate strabismus (<20 prism D), who retain peripheral binocular vision or even, abnormal binocular vision, disconjugate changes of saccades are driven by the disparity. Such changes help to maintain the state of binocular visual coordination around the endpoint of each new saccade. In contrast, for larger strabismus without binocular vision, disconjugate oculomotor changes are possible, but seem to be driven by monocular visual input. The changes serve to improve fixation of each individual eye rather than to reduce binocular disparity.

The main conclusion of this study is that the link between binocular vision and disconjugate oculomotor adaptation is looser than we initially thought. This has important clinical implications particularly for strabismic children. Visual binocular coordination, even if rudimentary, should be aimed for by clinicians. The disconjugate oculomotor adaptive capabilities which are necessary to compensate for the natural asymmetries and developmental changes of the oculomotor plants can be preserved in the presence of some binocular visual coordination. In turn, such compensation would allow patients to maintain, improve and stabilize the state of binocular visual coordination.

the disconjugacy occurred mainly during the saccade itself. In the present study, the changes in post-saccadic drift or in the static eye alignment were, in general, smaller in amplitude and not always in the correct direction. Schor *et al.* (1990), Henson & Dharamshi (1982) and Zee & Levi (1989) did induce adaptation of static eye alignment in addition to disconjugate adaptation of saccades and pursuit. These studies used longer training periods (several hours to several days) during which subjects exerted their normal activities, thereby stimulating all oculomotor subsystems. In our experiment subjects were requested to make saccades continuously and the training duration was 20 min only; this could account for our weak effects on static eye alignment.

The findings on subjects with small strabismus presented here, confirm that foveal fusion is not necessary to achieve disconjugate adaptation of saccade amplitude. In the following we will discuss the new information brought by this study on the relation between binocular vision and disconjugate oculomotor adaptive capabilities in strabismus pathology.

Intermediate strabismus

An important new finding is that fast disconjugate oculomotor adaptations are possible even for subjects with intermediate strabismus and pseudo or abnormal binocular vision (SH and WG). The squint was 18–21 prism D for both subjects and no normal binocular vision could occur. All stereoacuity tests (TNO, Titmus) were negative. Only at the synoptophore with large images and large disparities was some depth perception reported. What could be the basis of such rudimentary sensory binocular coordination? As mentioned, Bagolini (1974), 1982), supports the proposal that abnormal retinal correspondence is a sensory adaptation that allows binocular vision to occur in subjects with constant strabismus since childhood. Objective evidence supporting this hypothesis comes from studies of visual evoked potential (VEP). Binocular visually evoked potentials have shorter latency than monocular VEPs (binocular facilitation). Such binocular facilitation was found for strabismic subjects with abnormal retinal correspondence (Campos & Chiesi, 1983; Chiesi *et al.*, 1984). The idea of abnormal binocular vision with ARC is still controversial, however (for critical reviews see Von Noorden, 1990 and Schor, 1991). Nevertheless, at the clinical examinations, the visual capabilities of subjects SH and WG were clearly different from the other subjects (FH, PB, BM and TG), who did not show any evidence for binocular visual linkage. Similarly, the oculomotor adaptation to aniseikonia was different for subjects SH and WG than for subjects with larger strabismus. Thus, our oculomotor results support the idea of a rough binocular visual linkage in subjects with intermediate strabismus (<20 prism D) and abnormal retinal correspondence.

Our finding of changes in the disconjugacy of saccades in strabismics with feeble rudimentary binocular vision confirms and extends our prior conclusion that bifoveal fusion is not necessary to achieve disconjugate oculomotor adaptation. It is possible that rudimentary binocular visual coordination substitutes for real fusion in driving oculomotor disconjugate adaptations. Thus, our findings do not necessarily contradict earlier reports in monkeys with normal binocular vision (Oohira & Zee, 1992); in such subjects foveal fusion could be necessary to implement disconjugate oculomotor changes.

Large strabismus

Another important new finding is that disconjugate changes of saccade amplitude are possible, even for subjects with large strabismus with neither binocular vision nor stereoacuity. The changes, however, were not in the direction required by the aniseikonic images. Due to the corrective prism the squint angle of most subjects with large strabismus was smaller than 14 prism D, i.e. smaller than that of subjects SH and WG (Fig. 1). Yet, subjects without binocular vision failed to produce changes appropriate for the disparity due to aniseikonia. Could their changes be considered aberrant?

The reduction of the squint could encourage the eye under prism to pick up fixation more frequently, thereby improving its accuracy with respect to the target. To test this we examined the changes in the mean amplitude of the saccades of each eye for target fixations at 5 deg to the right. For subject PB before training, the mean saccade amplitude of the left, dominant eye was 5 ± 1.9 (SD, $n = 38$), while that of the right eye was only 2.9 ± 1.2 deg. After training the mean saccade amplitude increased significantly in the right eye that wore the prism (4 ± 0.86 $n = 22$); the amplitude of the left eye did not change significantly. For subject TG1 the amplitude of the saccade increased significantly in both eyes, albeit more in the left eye (LE: from 3.5 ± 0.8, $n = 21$ to 5.7 ± 1.12, $n = 23$; RE: from 4.3 ± 0.9 to 4.9 ± 0.8 deg). This was a combination of a conjugate and a disconjugate change. Subject FH also showed a significant increase of the amplitude of the saccades of the right eye that wore the prism, without significant change of the amplitude of the saccade of the left eye. Saccades before training from this subject were directed to 10 deg targets while saccades after training were directed to 5 deg targets. The ratio of the mean saccade amplitude/target position for the left eye was 1.05 and 1.16 before and after training; that of the right eye wearing the prism rose from 0.74 (before training) to 1.52 (after training). Thus, the changes in the inherent disconjugacy of saccades in subjects without binocular vision were not aberrant. They served to improve fixation of each individual eye, rather than to reduce binocular disparity.

In such subjects, disconjugate changes of saccade amplitude would be driven by monocular visual input and movements of the two eyes would be controlled independently. An elegant review of the concept of such "utrocular vision" (vision with each eye separately) independent eye movement control in strabismic subjects was presented by Schor (1991). As pointed out by this author, utrocular vision would be a primitive state of binocular vision found in vertebrates with complete

decussation of the visual pathways. The egocentric direction of the two eyes could be compared in a binocular sense; if the position and the direction of each eye are accurately computed then diplopia would never occur. Our oculomotor results (Fig. 2) show that the monocularly driven oculomotor changes leave uncorrected, and even create substantial additional, disparity. Yet, our subjects did not report diplopia; utrocular vision could allow avoidance of diplopia but not establishment of a real binocular linkage.

Our finding of changes in the inherent binocular coordination of saccades in subjects with large strabismus and no binocular vision is compatible with the observations of Maxwell *et al.* (1995). In this study, three subjects with intermediate strabismus (<20 prism D) but with deep unilateral amblyopia, and therefore, with no binocular vision, wore a spherical lens of −3 D in front of their amblyopic eye for a week. This caused a change in the inherent disconjugacy of their saccades. Maxwell *et al.* discussed the possibility of a recalibration of the vestibulo-ocular response by the differential retinal slip sensed by the two eyes during a week; vestibular recalibration would be carried over the saccadic system. Another possibility considered by these authors is the hypothesis of utrocular vision allowing independent readjustments for each eye.

Additional observations and remarks

In additional experiments we tested a subject with large divergent strabismus (−42 prism D) and mild unilateral amblyopia (corrected visual acuity RE 20/70, LE 20/40; spectacle correction was RE −11 diopters, LE −7 diopters). The inherent intrasaccadic disconjugacy was relatively small (<0.9 deg). Exposure to aniseikonic images (the 8% magnifier was placed on the left eye and a base-in prism of 40 prism D on the right eye), did not induce any change in the intrasaccadic disconjugacy, even though the prism reduced the squint angle to approx −10 diopters. In a second experiment, the squint was −34 prism D due to botulinum injection (done 10 months earlier). During exposure to aniseikonia (8% magnifier on the left eye) a base-in prism of 22 prism D on the right eye dropped the squint to −2 prism D. Despite his quasi-orthotropia, all the changes in intrasaccadic disconjugacy (2–3 deg large) were in the wrong direction. This supports the idea that at the adult stage, the deficiency of oculomotor adaptations is not related to the type (convergent or divergent) of strabismus, neither to the actual size of the squint. We think that the main reason for such oculomotor failure is the lack of binocular vision. Further support for this comes from our observations on another subject (27 years old) who had convergent strabismus since childhood (initial angle was 35 prism D) and deep amblyopia of the left eye (20/200); her right eye had normal visual acuity (20/20). She underwent eye surgery operation twice (at 7 and 15 yr), and botulinum toxin injection (done 1 yr before our oculomotor testing). At the time of our oculomotor examination her squint was reduced to 8 prism D (esotropia). However, the inherent disconjugacy of her saccades was remarkably large (4–6 deg), the right, non-amblyopic eye was making consistently larger saccades. These observations, admittedly based on one subject, suggest that binocular coordination of saccades is even more deteriorated in strabismics with severe amblyopia. She performed our oculomotor adaptation experiment with the 8% magnifier in front of her right eye. Not surprisingly, this subject did not respond to the disparity induced by the magnifier. Amblyopia in this subject was an additional factor responsible for the paucity of binocular visual linkage.

To recapitulate, we found evidence that at the adult stage, neither the actual size of the squint nor the type of strabismus (divergent or convergent) determine the adaptive oculomotor capabilities. Firstly, we found different oculomotor adaptive capabilities in subjects with small and large convergent strabismus, even though their squint angles were made similar (with the use of the prism). In addition, a subject with almost nullified divergent strabismus failed to adapt to aniseikonia. Furthermore, another subject with small residual convergent squint but deep unilateral amblyopia did not show any response to aniseikonia. One feature common to all these subjects who failed to adapt was a paucity of any binocular visual linkage. Most likely, binocular vision in such subjects could not be restored after wearing a prism for only 20–30 min. As Pigassou-Albouy & Garipuy (1966) reported, in adult strabismics, several months of prism therapy are needed for binocular vision to be restored.

Summary and clinical considerations

All strabismic subjects were capable of making disconjugate changes in their saccades. For subjects with small or intermediate strabismus (<20 prism D), who retain peripheral binocular vision or even, abnormal binocular vision, disconjugate changes of saccades are driven by the disparity. Such changes help to maintain the state of binocular visual coordination around the endpoint of each new saccade. In contrast, for larger strabismus without binocular vision, disconjugate oculomotor changes are possible, but seem to be driven by monocular visual input. The changes serve to improve fixation of each individual eye rather than to reduce binocular disparity.

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